Optical amplifiers

2011

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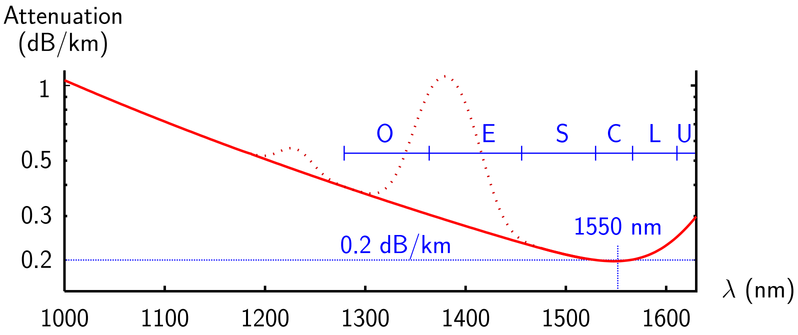
TELECOM ParisTech

Introduction

- High-speed wired communications: optical fibers
- Primary limiting factor: attenuation



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Introduction

- Avoid signal regenerators (O-E-O bulky; all-optical not mature)

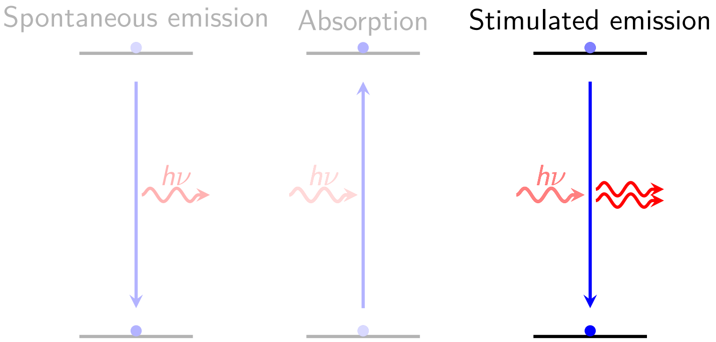
$\Rightarrow$ Optical amplifiers

  - since 1993: long-distance transmissions
  - 2000s: metropolitan networks
  - now: extended-range access networks
  - envisioned: all-optical signal processing

$\Rightarrow$ Transmission bandwidth = amplifiers' gain bandwidth

Optical amplification

Optical amplification based on stimulated emission:



Need more electrons in excited state than in fundamental state

$\Rightarrow$ population inversion

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Parameters of an amplifier

- Fundamental parameters:
  - λ, bandwidth
  - Gain, saturation / output power
- System / technological parameters:
  - Noise, signal distortion
  - Speed, transient management
  - Packaging, bulkiness, consumption
  - Cost
- Extra functionalities:
  - Dispersion compensation
  - Channel add/drop
  - Monitoring

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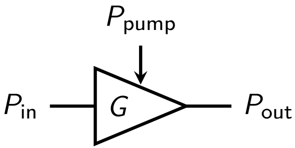
Gain and saturation

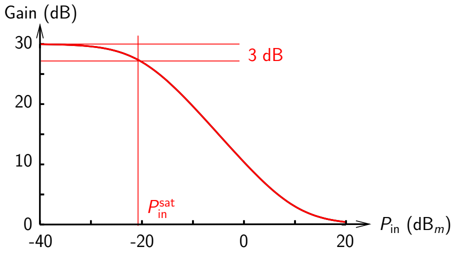
- Gain:

$$P_{\text{out}} = G P_{\text{in}}$$

$$P_{\text{in}} (G - 1) < P_{\text{pump}}$$



- Saturation / max. output power



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Amplification noise

- Amplifiers add noise (else violate uncertainty principle)
  - Amplified spontaneous emission (ASE)
  - Noise transfer from pump
  - Vacuum fluctuations ...

- Noise Figure:

$$NF = \frac{\mathrm{SNR_{in}}}{\mathrm{SNR_{out}}}$$ assuming quantum-noise-limited input signal

$$NF \geqslant 3\,\mathrm{dB}$$ (for a high-gain optical amplifier)

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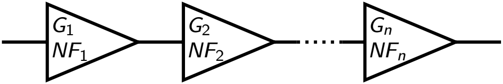
Noise from a chain of amplifiers

- Amplifier chain: the first amplifier's noise dominates



$$NF = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \ldots \text{ (Friis formula)}$$

(Not to confuse with transmission chain, which has strong attenuation between amplifiers)

- Attenuation: quantum noise not affected
  $\Rightarrow$ $NF(\text{attenuator}) = \text{attenuation}$
- Insertion loss: attenuation at amplifier input
  $\Rightarrow$ Strong influence on NF

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Signal distortions

- Dispersion (chromatic and polarization) in long amplifiers
- Polarization-dependent gain (PDG)
- High power $\Rightarrow$ non-linearity
  - WDM $\Rightarrow$four-wave mixing, crosstalk
  - Soliton-like pulse compression
- Gain saturation rapidity
  - Fast gain $\Rightarrow$ non-linearity, distorted bits
  - Slow gain $\Rightarrow$ modulation-transparent, problems with transients

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Packaging

- Pumping types
  - electrical $\Rightarrow$ easy integration
  - optical $\Rightarrow$ must insert pump, separate signal at output
- Packaging
  - all-integrated / discrete components
  - rackable units
  - bulkiness, electrical consumption
  - submarine cables: fit in cable, remote power supply...
- Integration
  - photoreceiver + preamplifier
  - loss-less splitter
  - active switching matrix

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Functionalities of amplifiers

- WDM amplification
  - Simultaneous amplification of λ comb
  - Gain equalization
- Gain control
  - Gain variation rapidity
  - Input power fluctuation handling
- Inter-stage access
  - Dispersion compensation
  - ROADM: channel add-drop
- Monitoring
  - Check operation
  - Optical power of individual λ channels
  - Channel estimation

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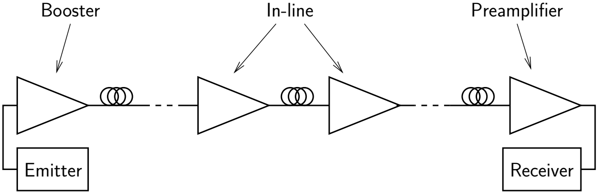
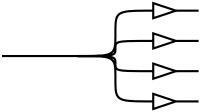
Typical usage configurations

- Transmission line



- … in a mesh network
  - Different channels → different paths
  - Variable traffic, packet network ⇒ power fluctuations
  - Reconfigurable channel add-drop (ROADM)
- “Loss-less” splitter: $1 \times N$ + integrated amplifiers



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Needs for different usages

	Transmission			Network	
	Booster	In-line	Preamp	Metro	Access
High gain	important	critical	critical		
High P_{out}	critical	important			
Low NF and insertion loss		important	critical		
Polarization independence	important	critical	critical	critical	critical
Bandwidth		wide	narrow		Coarse WDM
Dispersion mgmt		DCF		multi-span	
Add/drop				ROADM	
Low consumpt		important			important
Low cost				important	critical

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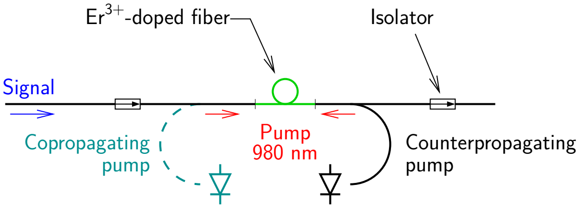
Erbium-doped fiber amplifiers

Currently most-used amplifiers: EDFAs

- Er^{3+} ions in silica (glass) fiber (codoped Al_2O_3, GeO_2, P_2O_5... possibly TeO_2 ou ZBLAN/fluoride → stronger doping)
- Optical pumping: 980 nm, used to be 1480 nm, more efficient before good 980-nm lasers
- Amplification in C-band (1530-1565 nm) or L-band (1565-1600 nm)
- Setup:



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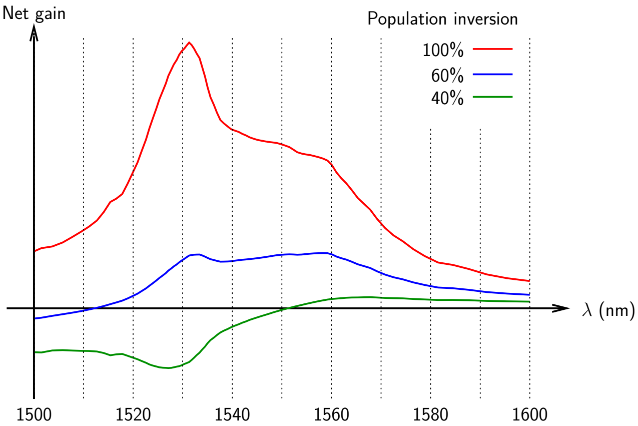
EDFA: gain spectrum



- Adjustement: pump power and λ, fiber length...
- Special-glass fibers (TeO_2, ZBLAN)
- Gain-flattening filters (GFFs)

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Gain-flattening filters

Gain-flattening filters → gain equalization

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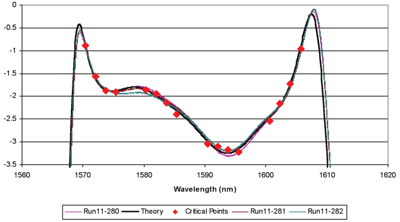
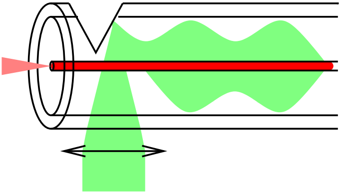


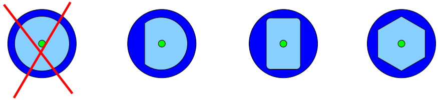
- Interference filters or Fiber Bragg gratings (FBGs)
- Complex design
- Sensitive → temperature variations
  - Active temperature control
  - Athermic packaging that compensates dilatation
- Insertion loss

  ⇒ Between stages (before input: NF ↗, after output: P_{out} ↘)

EDFA: pumping

- Single-mode fiber required for the signal
  - ⇒ low numerical aperture ⇒coupling losses when injecting
- Single-mode not needed for pump
  - ⇒ double-cladding fiber, V-groove injection (high-power amplifiers)





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EDFA characteristics

- C- or L-band
- All-fiber $\Rightarrow$ low insertion loss
- Gain up to 40 dB, $P_{\text{out}} > 23\,\text{dB}_\text{m}$, polarization-independent
- NF down to ~ 3 dB (lab) ; 4–6 dB in practice
- Long-lifetime excited states (few ms)
  - $\Rightarrow$ gain $=$ constant over each bit
  - $\Rightarrow$ good linearity
- Drawbacks:
  - Optical pumping $\Rightarrow$ complex
  - Sensitive to traffic fluctuations (on packet networks)

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Modern EDFAs

- Usage: all applications on C + L bands
- Dynamic gain equalization
- Power monitoring (not on individual WDM channels: too costly)
- 2+ stages, mid-point access → DCF, add-drop

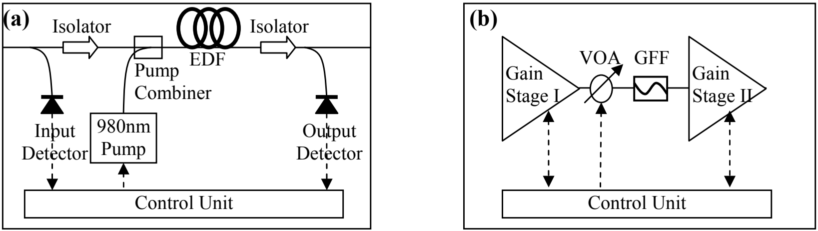
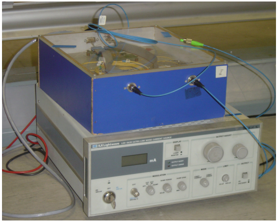
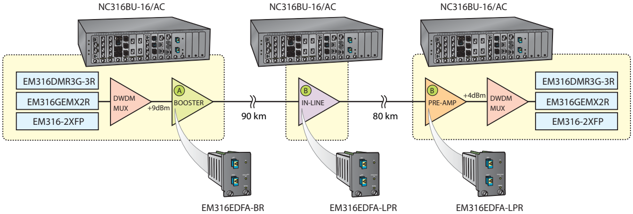


Figure 1. (a) Basic Single Stage Amplifier Module, (b) Broadband Variable Gain EDFA.

D. Menashe, *"Optical Amplifiers for Modern Networks"*, ICTON 2006.

EDFA packaging





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Other doped-glass amplifiers

Same principle as EDFAs:

- EDWA: doped waveguide instead of fiber
  - Short length (few cm), low bulk
  - Obsoleted by mini-EDFAs (fiber spool fits < 10 cm)
- EYDFA : codoping erbium-ytterbium
  - High output power (30–45 $\mathrm{dB_m}$)
  - Only part of C band (1540–1560 nm)
- Thulium amplifier (lab)
  - Tm^{3+} ions in fluoride glass
  - S-band amplification
    (Depending on pump: 700 nm, 800 nm, 1 µm, 1.4 µm, and/or 1.56 µm)
- Short-λ amplifiers (lab)
  - Praseodymium or neodymium $\rightarrow$ O-band
  - Ytterbium $\rightarrow \lambda \sim 1\,\mu\mathrm{m}$

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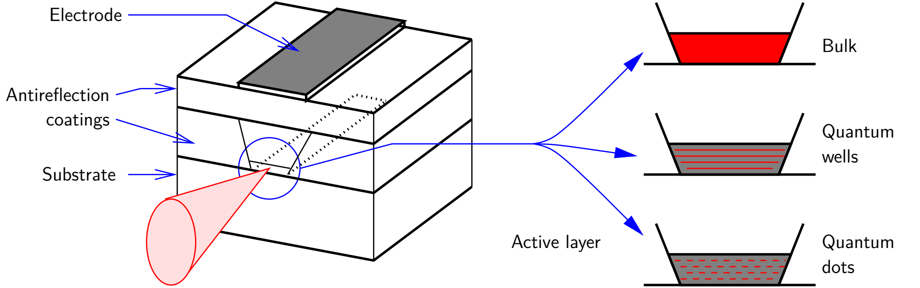
Semiconductor optical amplifiers

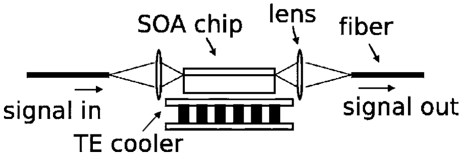
SOA = semiconductor laser without cavity
→ Fabry-Perot laser + antireflection-coated facets



SOA packaging

SOA module:

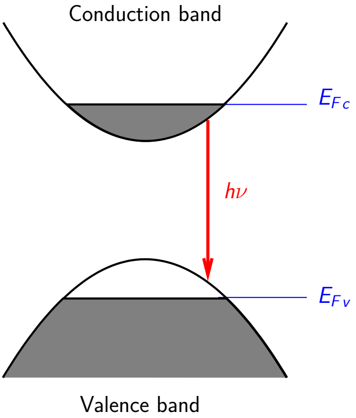
- chip mounted on base
- bias current 200 mA – 2 A (according to active layer volume)
- Peltier thermoelectric module → cooling, temperature control
- lensed fibers or microlenses

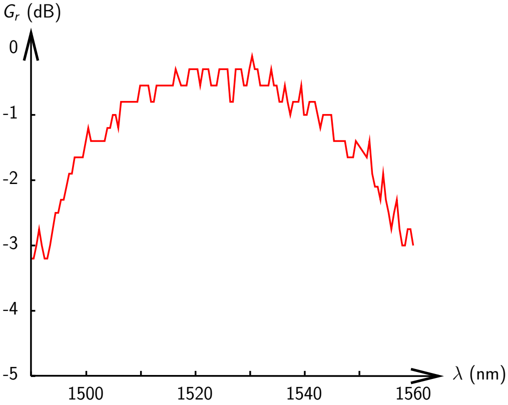


L. Spiekman, *"Semiconductor optical amplifiers for reconfigurable optical networks"*, J. Optical Networking 6 (11), Nov 2007.

SOA characteristics

Gain determined by energy band structure





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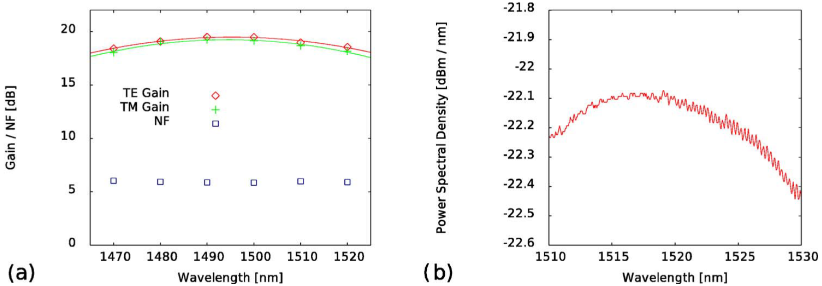
Bulk SOAs

Bulk / quantum-well (QW) SOAs:

- Mature technology, same wavelengths as lasers
- $G \sim 20\,\mathrm{dB}$, BW $> 50\,\mathrm{nm}$, NF $\sim 6\,\mathrm{dB}$
- Low polarization dependency, low ripple
- $P_{\mathrm{sat}} < 20\,\mathrm{dB_m}$, $\tau \sim 100\,\mathrm{ps}$–$1\,\mathrm{ns}$; nonlinearities

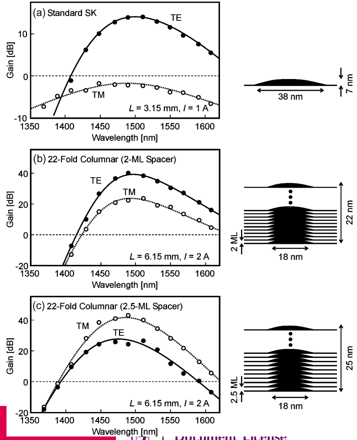


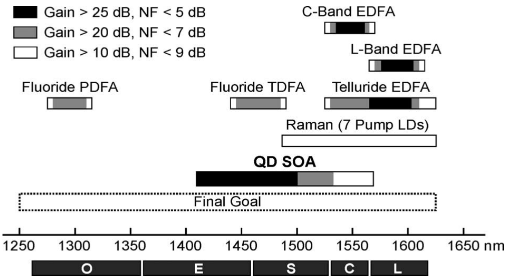
L. Spiekman, *"Semiconductor optical amplifiers for reconfigurable optical networks"*, J. Optical Networking 6 (11), Nov 2007.

Quantum-dot SOAs

Quantum-dot (QD) SOAs:

- $G \sim$ 10–25 dB, BW $\sim$ 100 nm, $\tau \sim$ few ps
- Excellent linearity
- Development underway; almost mature $\rightarrow$ C-band



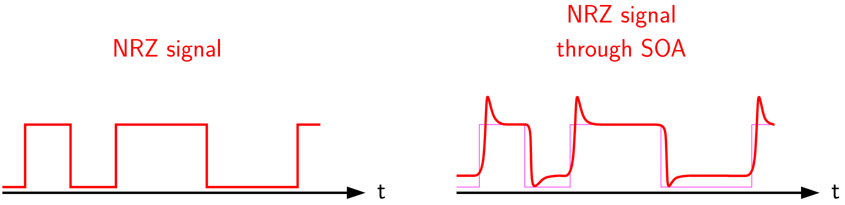


T. Akiyama et al., *"Quantum-Dot Semiconductor Optical Amplifiers"*, Proc. IEEE 95 (9), Sept 2007.

SOAs: poor amplifiers

Historically, SOA problems:

- SOA fast ($\sim 1\,\mathrm{ns}$) $\Rightarrow$ bit-timescale signal distortions



- Nonlinearities, four-wave mixing $\Rightarrow$ problem with WDM

$\Rightarrow$ EDFA preferred, except:

- Niche: transmissions outside C-band
- Niche: integrated amplifiers (e. g. with photodiode)
- Active MZI gates
- Signal processing: λ conversion, regeneration...

SOAs: comeback

Currently, SOAs making a comeback:

- Long-distance transmissions changing techniques
  - Constant-envelope modulations (NRZ-xPSK)
  - Packet networks $\Rightarrow$ transients on packet timescales
- Development of novel metro+access networks
  - Low cost preferred
  - Coarse WDM $\Rightarrow$ less FWM, need wide bandwidth
  - Shorter distances/lower powers $\Rightarrow$ small signals $\Rightarrow$ SOAs $\sim$ linear
  - "Extender-boxes" $\rightarrow$ long-range access networks ($>$ 20 km)

SOA improvements

- Quantum-dot SOAs:
  - Very wide bandwidth
  - Ultrafast electron transitions + wetting layer ⇒ gain is clamped
- LOA: SOA + VCSEL
  - Active layer sandwiched between Bragg reflectors
  - ⇒ Laser perpendicular to signal propagation
  - ⇒ Clamps carrier density ⇒ better linearity

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New SOA usages

- "Novel functionalities" of the 1990s (nonlinear effects)
  - All-optical signal processing
  - Wavelength conversion
  - Modulation format conversion
  - Regeneration
  - Logic gates

  → Still not widespread outside labs
- Integration / use as on-off switch
  - Loss-less splitters
  - Switching matrices
  - RSOAs: replaces laser + modulator for wavelength-independent optical network units in access networks

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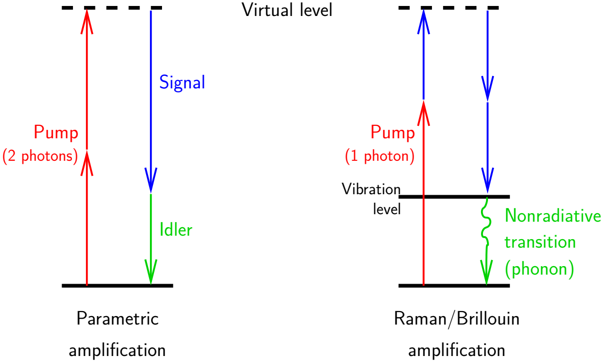
Nonlinear effects (for amplification)

- Several-photon interactions
- Interactions with non-electronic energy levels: phonons

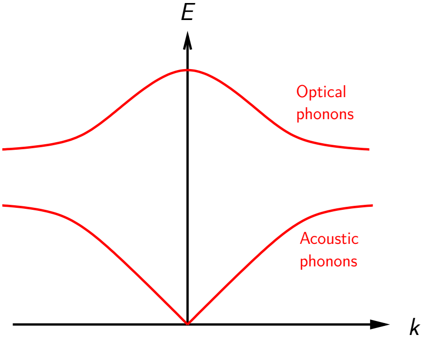


Conservation of energy & momentum:

$$\omega_p = \omega_s + \omega_{\text{phonon}}$$
$$\vec{k}_p = \vec{k}_s + \vec{k}_{\text{phonon}}$$

Phonon types

- Acoustic phonons: lattice vibrations, low frequencies
  $\rightarrow$ Brillouin effect
- Optical phonons: molecular vibrations, high frequencies
  $\rightarrow$ Raman effect



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Brillouin scattering

- Phase matching: $k_{\text{phonon}} \propto \omega_{\text{phonon}}$ thus, for significant frequency difference (hence gain), need large k_{phonon}.

$\Rightarrow$ counterpropagating pump ($-k_p = k_s - k'_{\text{phonon}}$).

- Very narrow bandwidth: few 10 MHz.

$\Rightarrow$ Application: possibly low-bitrate WDM demultiplexing.

$\rightarrow$ Mostly, parasitic effect that limits optical power.

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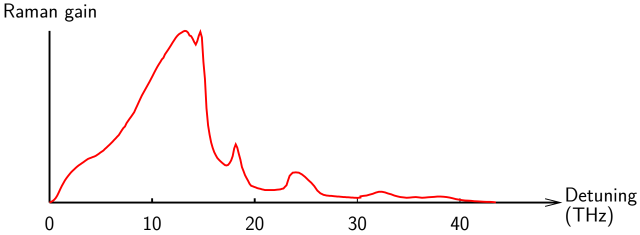
Raman amplification

Raman-effect fiber amplifier (RFA): same setup as EDFA, but the "active" fiber is a standard, long fiber, and λ_{pump} chosen as a function of λ_{signal}.



Gain peak: $\Delta\nu \sim 12\,\text{THz}$ ($\Delta\lambda \sim 100\,\text{nm}$).

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Pum configuration

- Phase matching: k_{phonon} may be large or small compared to k_{opt} for similar frequencies, so pumping can be copropagating $(k_p = k_s + k_{\text{phonon}})$ or counterpropagating $(-k_p = k_s - k'_{\text{phonon}})$
- But: very fast effect $\Rightarrow$ transfers pump noise to signal
- If counterpropagating pump, noise ends up averaged over each bit

$\Rightarrow$ Counterpropagating pump

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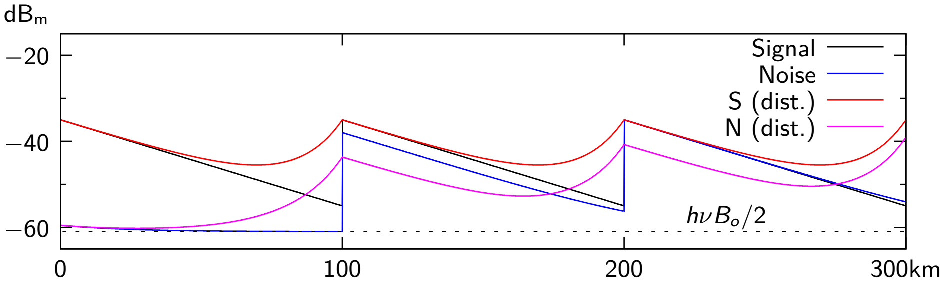
Raman amplifier = distributed amplification

- Localized amplifiers: between fiber spans
- Distributed amplifiers: gain along tail of transmission

$\Rightarrow$ less attenuation noise, better overall noise figure.



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Pros/cons of Raman amplification

Pros:

- Works at any λ
- Distributed amplification $\Rightarrow$ better NF
- Dual pumping $\Rightarrow$ gain over whole transmission span

Cons:

- Non-uniform gain
  $\Rightarrow$ Multiple pumps
- Need long fiber for significant gain
  $\Rightarrow$ directly over transmission fiber

$\Rightarrow$ Usage: in-line amplification.

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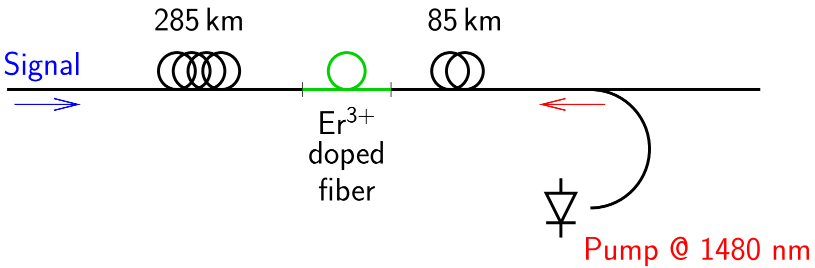
Hybrid Raman–EDFA amplification

Pump $\sim$ 1460–1480 nm, standard + doped fibers:
C-band EDFA + Raman

$\Rightarrow$ 2.5 Gbps over 370 km with single amplifier stage



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Amplifiers vs applications

Current usages:

- EDFAs mature $\rightarrow$ all telecom applications
  - installed in $\sim$ all amplified networks
  - only C and L bands; require control $\rightarrow$ transients
- Raman $\rightarrow$ long-range transmissions
  - deployed in recent systems
- SOA $\rightarrow$ low cost
  - beginning to be used

Under development:

- SOA $\rightarrow$ special functions (RSOAs; all-optical processing)
- QD-SOA: very promising
  - catch up with EDFA when available in C band?

Research or non-telecom usages:

- EYDFA (high power); Tm, Pr, Yb ($\lambda < 1500\,\mathrm{nm}$)

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References, further reading

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